The Importance of In-Vehicle Exposures

Presentation to the Board

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Good morning chairman Lloyd and members of the Board. My talk today will discuss the exposures to air pollution we receive while in vehicles and how much these contribute to overall exposures. For vehicle-related pollutants such as diesel PM, this contribution is quite significant, although we do not frequently measure it.

Outline

- **Overview of in-vehicle exposures**
- **In-vehicle studies conducted in CA**
  - **In-vehicle diesel PM exposures calculated from black carbon measurements, 1997 chase study[1]**
  - **Ultrafine particle exposures from 2003 measurements on LA freeways[2]**
- **Implications of in-vehicle exposures**
- **Measures of progress**

[1]Rodes et al., 1998; Fruin et al., 2004
[2]Westerdahl et al., 2004

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First I will provide an overview of in-vehicle exposure findings and demonstrate not only how significant they are, but also why they are so high.

Next I will briefly discuss several in-vehicle studies conducted in California and their use in estimating in-vehicle exposures.

Finally, I will summarize the implications of these studies, including what they tell us about exposure reduction potential and our progress.

Overview of In-Vehicle Concentrations

- **Air exchange rates in vehicles high**
- **Concentrations:**

In-Vehicle = Centerline > Roadside >> Ambient

Examples of in-vehicle-to-ambient concentration ratios:

Benzene: 4 to 8 times higher[1]

Diesel PM: 5 to 15 times higher[2]

1,3-butadiene: 50 to 100 times higher[3]

[1]Rodes et al., 1998
[2]Fruin et al., 2004
[3]Duffy and Nelson, 1997

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Vehicles are not built to be air tight. The pressure changes around a moving vehicle can lead to dozens of air exchanges per hour, even if windows are closed. By comparison, a home typically has only one or two air exchanges per hour.

Another major aspect of in-vehicle exposures is that roadway concentrations of vehicle-related pollutants are typically several times higher than ambient concentrations. Furthermore, concentrations at the centerline of the road are highest, and can be several times higher again than concentrations on the side of the road. It is these centerline concentrations that reflect the air getting into your vehicle.

For example, using results from an ARB-sponsored study in Sacramento and Los Angeles in late 1997, aromatic compounds like benzene were 4 to 8 times higher inside vehicles than in ambient urban air.

For vehicle-related pollutants that have no evaporative component, the in-vehicle-to-ambient ratio is often higher. For example, diesel PM concentrations inside vehicles are believed to be 5 to 15 times higher than ambient, based on black carbon measurements.

Compounds with short atmospheric lifetimes appear to have the highest concentration ratios, such as 1,3 butadiene.

Overview of In-Vehicle Exposures

- **~90 minutes per day in vehicles**

- **Benzene: 15-20% of total exposure (LA)[1]**
- **Diesel PM: 30 - 55% of total exposure (CA)[2]**
- **1,3-butadiene, ultrafine particles: likely > 50%**

- **6% of day driving can give up to half of our exposures**

[1,2] Fruin et al., 2001; 2004

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These high in-vehicle concentrations contribute a lot to a person's overall exposure.

On average, Californians spend about 90 minutes per day in vehicles. This is about 6% of our 24-hour day. For a compound with multiple sources like benzene, the in-vehicle fraction of total exposure is 15 to 20%.

For pollutants like diesel PM the fraction is 30 to 55%.

Finally, the fraction for shorter-lived pollutants such as 1,3-butadiene or ultrafine particles may be even higher.

Therefore, although we spend only about 6% of our day driving, we get up to half of our exposures to vehicle-related pollutants during that time.

Estimating In-Vehicle Diesel PM Exposures

- Sacramento and Los Angeles, 1997
- Real-time measures of fine particle counts and black carbon
- Diesel vehicle chase-study design

Charles Rodes et al., 1998. RTI, Sierra Research, Aerosol Dynamics; SCAQMD co-funding

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These high fractions of overall exposure can be demonstrated from the ARB-sponsored exposure study of 1997.

This study was conducted by the Research Triangle Institute, and was one of the first_studies to use real-time instruments to measure diesel-related pollutant concentrations inside vehicles.

Real-time black carbon was measured, which is a sensitive indicator of diesel PM. Although it is not an unambiguous marker for diesel PM in ambient air, it is on roadways, because diesel vehicles are by far the dominant source.

The study focused on following diesel vehicles where possible. We call this a “chase study.” In order to use the study results to estimate actual diesel PM concentrations during typical driving, the black carbon measurements had to be dis-aggregated into components and re-constructed statistically.

Average Black Carbon Concentration behind Different Vehicle Types, LA:

Vehicle Type Followed	Black carbon (µg/m³)	Number of vehicles
(Urban background)	~1	
(Roadway background)	4.8	
Diesel tractor trailer	13	47
Diesel transit bus, high exhaust	16	12
Diesel passenger car (PC)	19	8
Gasoline-powered PC, smoky	19	6
Diesel transit bus, low exhaust	95	16
Highest emitter observed	>400	

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It turns out the dominant factor affecting in-vehicle black carbon in this study was the type of vehicle followed. Impacts varied by more than two orders of magnitude.

Roadway backgrounds were about 5 µg/m³, several times higher than urban background.

On average, gasoline-powered passenger cars had no black carbon contribution. However, if a gasoline-powered passenger car showed visible smoke, it generated similar black carbon impacts as a diesel-powered car, but this was fairly rare.

The physical configuration of the vehicle and the location of the exhaust was also an important factor. For example, vehicles with exhaust close to the ground at the back of the vehicle, such as diesel passenger cars, caused higher in-vehicle black carbon than tractor trailer big rigs, which have the exhaust located high at the front of the vehicle.

A direct comparison of exhaust height effects can be seen by comparing the different impacts of exhaust height for the transit buses, shown in red.

In-Vehicle Diesel PM Concentrations: Realistic-Driving Conditions

- **High congestion: 11 to 33 µg/m³ (LA and Bay Area)**
- **Moderate congestion: 6 to 17 µg/m³**
- **5 to 15 times calculated ambient concentrations**
- **30 to 55% of total diesel PM exposure**
  - **In-vehicle time most important route of exposure on a per-time basis**

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Most people will not purposefully follow a diesel vehicle if they have a choice.

To correct for following diesel vehicles more often than what would be typical, the data were disaggregated by type of vehicle followed under various road and congestion conditions. They were then randomly sampled and reconstructed using representative fractions of time spent driving under those conditions. For congested areas such as Los Angeles or the Bay Area, DPM concentrations of 11 to 33 µg/m³ were derived. Smaller cities such as Sacramento had about half those concentrations.

The concentrations from simulating realistic driving were only about a third of the actual chase study concentrations, but were still 5 to 15 times higher than ambient concentrations.

When diesel PM concentrations in other microenvironments were added to the analysis, and combined with studies of where people spend their time, the in-vehicle exposures appeared to contribute from 30 to 55% of total exposure.

At 6% of your day, the time spent in vehicles is obviously the most important route of diesel PM exposure on a per time basis.

1997 In-Vehicle Exposure Results

- **On-road diesel PM emissions very effective at producing exposures**
- **On-road reductions yield 2 to 5 times more health benefit than equal off-road reduction**

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One interesting implication of these results is that on-road emissions are much more effective at producing exposures than off-road emissions. This is because the majority of diesel PM emissions occur off-road, but contribute little to exposures compared to on-road emissions.

Reducing a given mass of on-road emissions produces 2 to 5 times the health benefits that an equal reduction in off-road emissions would produce.

2003 Field Study Route

Continuous pollutant measure-ments:

Black carbon, ultrafine particles, NO, NO_2, CO, CO_2, particle-bound PAHs, PM2.5

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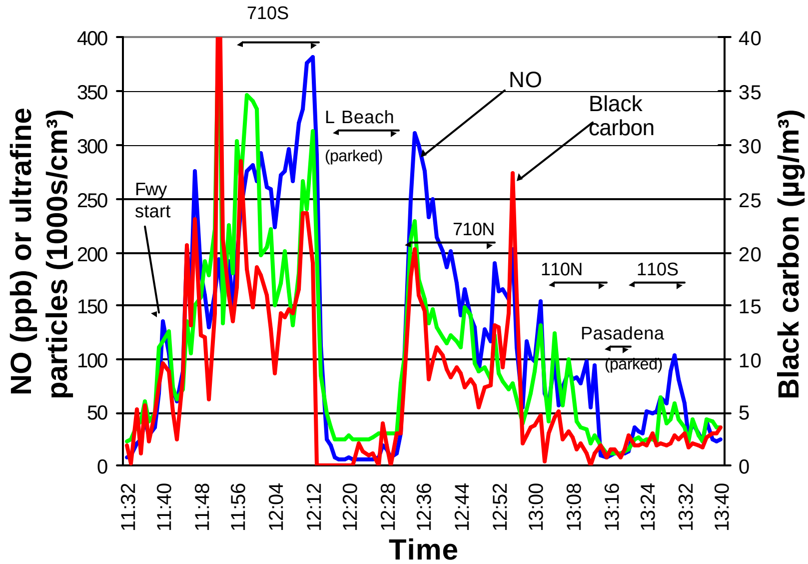
The next study was carried out in Los Angeles in 2003 by staff in Research Division, including Dane Westerdahl and myself. We followed the route shown. This included freeway driving on the 710 to Long Beach, known for its high truck traffic from the port, as well as the 110 freeway north to Pasadena, with almost no diesel traffic on its northern portion.

The pollutants listed on the right were all measured continuously during runs.

Time Series: NO, Ultrafine Particle Number, and Black Carbon



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Here are typical concentrations during the 75-mile-long route, which took just over two hours.

You can see the high correspondence between ultrafine particle counts, black carbon, and NO. The first peak on the left corresponds to getting on the 110N freeway near the USC campus.

The area of highest concentrations on the left correspond to time on the 710 south freeway, followed by a sharp drop immediately upon exiting this freeway at Long Beach. The region of low concentrations occurred during parking on a residential street. The next rise corresponds to the trip back, including time on the 110, a freeway with light truck traffic. The time parked on a Pasadena side street is the next low point.

Overall, the pollutant concentrations between freeway and low-traffic residential areas reflected about a hundred-fold difference.

Some of the concentration spikes you see represent high-emitters, but in this case driving neither chased nor avoided any particular vehicle.

High Emitter of Black Carbon, PM2.5

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Here is a visual example of a high-emitting diesel vehicle, almost obscured by smoke, in front of the delivery truck on the right. This produced very high black carbon and PM mass, but only moderately high ultrafine particle counts.

High Ultrafine Particle Emitter

Diesel truck, no visible emissions

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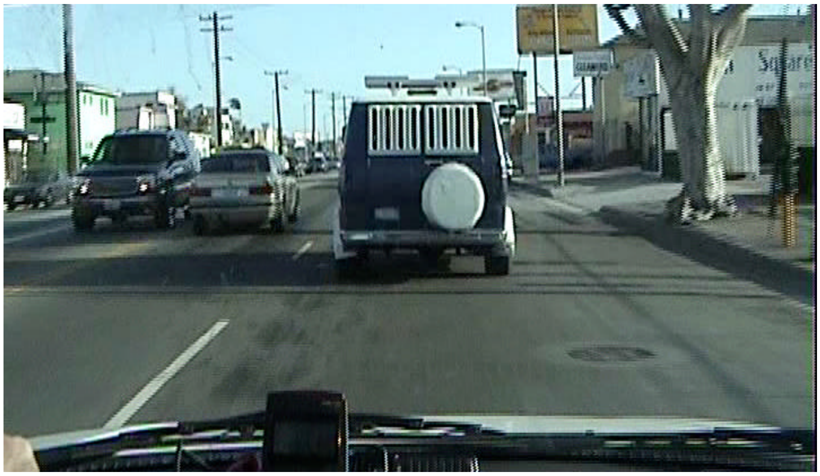
High black carbon or high mass emitters are generally quite visible. In contrast to the previous smoky truck, this mid-80s Ford truck produced no visible emissions but was one of the highest emitters of ultrafine particles observed.

These two examples illustrate how different vehicles can be high emitters of different pollutants, and that high ultrafine emissions are not visible.

High Ultrafine Particle Emitter

Gasoline-powered van



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Here is another high ultrafine particle emitter, this time a gasoline-powered van. Out of tune and older gasoline-powered vehicles and gasoline vehicles undergoing hard accelerations can also produce high emissions of ultrafine particles.

Average In-Vehicle Concentrations for Four Days

Location or roadway	Ultrafine particle conc. (#/ cm^3)	NO (ppb)	Black carbon (µg/m^3)	CO_2 (ppm)	Avg. min. per run
Residential Street (Long Beach)	27,000	19	1.4	420	14
110N freeway near Pasadena (~300 trucks/day)	43,000	150	1.6	770	15
110N freeway (~3000 trucks/day)	67,000	230	3.9	850	10
710S freeway (~25,000 trucks/day)	200,000	400	14	850	21

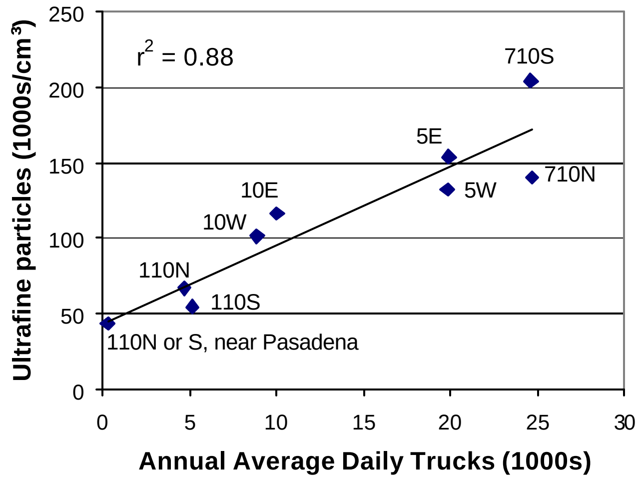
These concentration averages are from four freeway circuits on four different days.

Concentrations of ultrafine particle counts, NO, and black carbon all increase by over an order of magnitude from the residential area of Long Beach at the top of the chart to the high truck traffic of the 710 freeway.

The ultrafine particle concentrations on the 710, at 200,000 per cubic centimeter, are two hundred times greater than inside the Cal/EPA building. That means twenty minutes on the 710 would take nearly three days to equal inside this building.

CO2 increases are also interesting. Long Beach at 420 ppm is not far above the global background of about 375 ppm, but concentrations increase markedly on all roads, even arterial roads.

Ultrafine Particle Number by Freeway Segment versus Average Daily Truck Count



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When ultrafine particle counts are plotted against the annual average daily truck counts made by the California Department of Transportation,CalTrans, the relationship is remarkably linear. Truck volumes and emissions on average appear consistent enough to be predicted by already compiled truck count measures.

In contrast, total traffic volumes, or traffic conditions such as speed or congestion, were much less predictive of ultrafine particle concentrations.

In-Vehicle Fraction of Total Ultrafine Particle Exposure

- **Average ultrafine particle number and time spent:**

Location	Time (Hrs)	Concentration (1000s/cm³)
Residential	9	2 (night)[1]
Residential	5.5	5 (evening)[1]
Workplace	7	5
Outdoors	1	20
In-vehicle arterial	1	50
In-vehicle freeway	0.5	150

- **>50% exposure from in-vehicle time**

[1]Wallace et al., 2004

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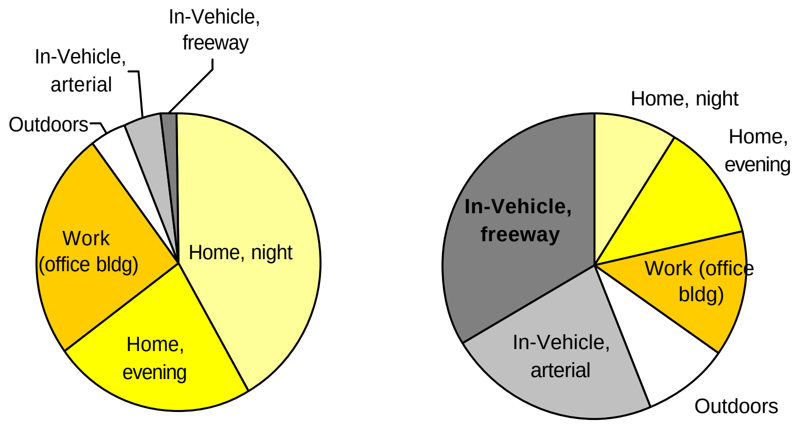
To estimate the contribution of in-vehicle ultrafine particle concentrations to total exposure, for a typical LA resident we can use the following typical concentrations and average times spent in those environments.

For these concentrations, the in-vehicle time contributed 54% of total exposure, similar to the upper end of the diesel PM estimates.

In-Vehicle Fraction of Total Ultrafine Particle Exposure



Average Time Spent **Contribution to Exposure**

Illustrated another way, the pie chart on the left shows typical time spent, with indoor environments in yellow and in-vehicle environments in gray.

The chart on the right shows the dominant role played by in-vehicle time on ultrafine particle exposure.

The time you spend on freeways, especially during your commute, and the volume of truck traffic will strongly influence this fraction.

In-Vehicle Studies as Measure of Progress

- **Similar to tunnel studies**
- **Gasoline-powered vehicle success:**

  1987 ambient VOC concentrations in LA[1] ~ 1997 in-vehicle concentrations[2]

- **Diesel-related:**

  Results more mixed

[1]Shikiya et al., 1989
[2]Rodes et al., 1998

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Besides being important in calculating exposures, on-road measurements are a good way to determine our progress in reducing vehicle emissions. Like tunnel studies, they represent large sample sizes, but can also cover large geographic areas.

The reductions in gasoline-powered vehicle emissions can be seen in comparing the in-vehicle study of the late 80s by South Coast AQMD, one of the first in-vehicle studies conducted, and the 1997 ARB study. Here, the ambient VOC measurements from the South Coast study in the late 1980s matched the in-vehicle VOC concentrations in the late 90s.

This indicates great progress in cleaning up gasoline-powered vehicles during the 1990s.

For diesel-related pollutants, results between 1997 and 2003 appear more mixed, but we now have good baselines from which to measure future progress when the 2007 fuel and diesel vehicle standards begin to take effect.

Take Home Messages

- **In-vehicle exposures important to overall exposures to vehicle-related pollutants**
- **Ultrafine particle exposure depends on:**
  - **Length of your commute**
  - **Diesel truck volumes**
  - **Types of vehicles followed**

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The primary messages from this presentation are the importance of in-vehicle exposures and their large contribution to total exposure for vehicle-related pollutants.

The length of your commute and the conditions under which it occurs can strongly affect your exposures. The volume of diesel traffic appears to be a key driver for pollutants like ultrafine particles. In addition, the short-term effects of following particular vehicles can be quite high.

Take Home Messages

- **Location of emissions matter:**
  - **On-road emissions produce greater overall exposures than off-road**
  - **Exhaust at low and rear of vehicle produces greater in-vehicle impacts than exhaust at high and front of vehicle**
- **Reductions in on-road diesel emissions are critical to reducing in-vehicle exposures**

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Finally, the locations emissions occur matter. On-road emissions produce greater exposures than off-road, and low exhaust locations have higher impacts than high exhaust.

Therefore, when you consider the contributions of in-vehicle exposures to total exposure, reductions in on-road diesel emissions are by far the most effective way to reduce peoples exposures to vehicle-related pollutants.

Do In-Vehicle Particles Play an Important Role in Heart Disease?

- Recent study found association with being in traffic and heart attack in following hour[1]
- Study of North Carolina troopers found changes in cardiac rhythm and blood markers of inflammation and coagulation[2]
- Proposed ARB study of ultrafine particles from freeway driving and cardiovascular and blood marker symptoms

[1]Peters et al., 2004
[2]Reidiker et al., 2004

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As ambient air particulate matter has been linked to increased incidence of heart disease, one are of growing research is investigating the possible links between in-vehicle particle exposures and heart disease.

One recent study found an association between being in traffic and greater risk of heart attack in the following hour. Another study found cardiac rhythm changes and blood effects in North Carolina troopers after their shifts.

One ARB study proposed for next year will investigate the effect of ultrafine particle exposures during freeway driving on cardiovascular and blood markers.

This concludes my presentation. I'll be happy to answer any questions...